# Study of Influence of Tool Nose Radius on Surface Roughness and Material Removal Rate in Turning of Inconel 718 by using Taguchi Grey Relational Analysis

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**Abstract -** *In the manufacturing industry, turning process is one of the most fundamental cutting processes used. Surface roughness and Material Removal Rate are the main quality functions in turning of Inconel 718 in dry conditions. The present work focuses on an experimental study to find the effects of insert nose radius and cutting parameters on surface roughness and material removal rate. The optimization of two response parameters (Surface roughness and Material Removal Rate) by four machining parameters (cutting speed, feed rate, depth of cut and nose radius) is investigated for better surface finish and high Material Removal Rate (MRR) during turning of Inconel 718. A combined Taguchi method and Grey Relational Analysis (GRA) is used for the optimization. Analysis of Variance (ANOVA) is employed to find out contribution of each parameter. Four parameters are chosen as process variables: cutting speed, feed rate, depth of cut and nose radius each at three levels. The experiment plan is designed using Taguchi's L9 Orthogonal Array (OA). Minitab statistical software is employed to create the plan and carrying out the analysis. The effects of various parametric combinations on the turning process are studied and an optimization strategy for a given set of parameter combination for better surface finish of the turned product is developed. The results show that feed rate and nose radius are the most important parameters that affect the surface finish and Material Removal Rate (MRR) in CNC turning process is greatly influenced by depth of cut followed by cutting speed. A prediction model is also developed separately for both surface finish and MRR using multiple regression analysis.*

***Key Words*:** Optimization, ANOVA, MRR, Surface Roughness, Taguchi Method, Grey Relational Analysis (GRA), Orthogonal Array (OA).

## 1. INTRODUCTION

Good machinability can be defined as an optimal combination of factors such as low cutting force, good surface finish, low power consumption, high material removal rate, accurate and consistent work piece geometrical characteristics, low tool wear rate and good chip breakdown of chips. Dimensional accuracy, tool wear and quality of surface finish are three factors that manufacturers must be able to control at the machining operations to ensure better performance and service life of engineering component [1].

In recent manufacturing trends, manufacturers are facing few important challenges like higher productivity, quality, overall economy and customer satisfaction in the field of manufacturing by machining. To meet the above challenges in a competitive manufacturing environment, there is an increasing demand for high material removal rate (MRR), higher surface finish and stability of the cutting tool but high production with high cutting speed, feed and depth of cut generates large amount of heat and temperature at the chip-tool interface which ultimately reduces dimensional accuracy, tool life and surface integrity of the machined component [2].

It is necessary to select the most appropriate machining parameters in order to improve cutting efficiency, process at low cost, and produce high quality products. The challenge of modern machining industries is mainly focused on the achievement of high quality, in term of work piece dimensional accuracy; surface finish. Surface roughness consists of the fine irregularities of the surface texture, including feed marks generated by the machining process. The quality of a surface is significantly important factor in evaluating the productivity of machine tool and machined parts. The surface roughnesses of machined have considerable influence on properties such as wear resistance and fatigue strength. It is one of the most important measures in finishing cutting operations [2].

### 1.1 INCONEL 718 Alloy

Inconel 718 is a Gamma Prime (Ni3Nb) strengthened alloy with excellent mechanical properties at elevated temperatures, as well as cryogenic temperatures. Inconel 718 is used in any environment that requires resistance to heat and corrosion but where the mechanical properties of the metal must be retained. The challenge and difficulty to machine Inconel 718 is due to its profound characteristics such as high shear strength, tendency to weld and form build-up edge, low thermal conductivity and high chemical affinity. Inconel 718 also has the tendency to work harder and retain major part of its strength during machining. Due to these characteristics, Inconel 718 is not easy to cut and thus has been regarded as a difficult-to-cut material. Inconel 718 being a difficult-to-machine material requires hard cutting tool [10, 12].

Inconel 718 is a super alloy which is widely used in the hot sections of aviation components. It contains niobium, an age-hardening addition that provides increased strength and corrosion resistance without decrease in ductility. The alloy has excellent creep-rupture strength at temperature up to 700°C. Hence it is widely used in gas turbines, aircraft, rocket motors, spacecraft, nuclear reactors etc. Table 1 shows chemical composition of Inconel 718 alloy.

**Table -1:** Chemical composition of Inconel 718

| Elements | Ni(+Co) | Mo | Ti | C | Si | Cu | Cr | Co | Nb(+Ta) | Al | Mn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Percentage (%) | 50-55 | 2.3-3.3 | 0.6-1.15 | 0.08 | 0.35 | 0.3 | 17–21 | 1 | 4.75 - 5.5 | 0.2-0.8 | 0.35 |

## 1.2 Objectives of work

1. Measurement of experimental observations for surface roughness and material removal rate under various conditions.
2. The main objective of this work is to study the influence of machining parameters i.e. speed, feed, depth of cut and tool geometry i.e. insert nose radius on surface roughness (SR) and material removal rate (MRR) of turned part of Inconel 718.
3. To develop optimization strategy for given set of input parameter combination for better surface finish and high material removal rate using combined Taguchi and Grey Relational Analysis (GRA).
4. To perform verification by prediction model and confirmation test.

## 2. EXPERIMENTAL SETUP

In this work L9 orthogonal array is selected for four parameters namely cutting speed, feed rate, depth of cut and nose radius, each at three levels shown in Table 2 .The values of the process parameter levels are selected according to the data available from the previous literatures, experienced personals, from the tool manufacturer's information, etc.

**Table -2:** Parameter Levels

| Levels | Parameters | | | |
|---|---|---|---|---|
| | Cutting speed (RPM) | Feed rate (mm/rev) | Depth of cut(mm) | Nose radius(mm) |
| Level 1 | 225 | 0.10 | 0.1 | 0.4 |
| Level 2 | 470 | 0.15 | 0.3 | 0.8 |
| Level 3 | 715 | 0.20 | 0.5 | 1.2 |

A bar of Inconel 718 with diameter 30 mm and length 350 mm (Figure 2) is used for the experiment. The work piece is initially prepared on a CNC lathe machine by providing an initial facing and turning to make diameter 29 mm to remove irregularities and impurities on skin of raw material bar of Inconel 718.

Latest Aluminum (Al) coated carbide inserts with different nose radius 0.4, 0.8 and 1.2 mm (Figure 1) was used for the machining purpose. It is observed that carbide tools are most suited for machining Nickel alloys [7]. Three inserts of different nose radius and same grade TNMG160404 MSMP9015, TNMG160408 MSMP9015, TNMG160412 MSMP9015 (Made: MITSUBISHI) are used. The tool holder MTJNR2020 K16N (Made: MITSUBISHI) is selected according to the type of insert used.

0.4 mm 0.8mm 1.2mm

**Fig -1:** Photographic view of inserts

**Fig -2**: Photographic view of Inconel 718 bar

## 2.1 Experimental Procedure

The machining is done on a 2 axis HAAS TL1 CNC lathe (Figure 3). The work piece was mounted on a pneumatic chuck and the CNC program for machining is entered according to the selected parameters. A simulation check is done for each run to avoid errors in program and machining. The turning process is carried out according to the experimental chart designed using the orthogonal array.


**Fig -3**: CNC lathe turning centre


**Fig - 4:** Surface Roughness Tester

## 3. RESULTS AND DISCUSSIONS

Nine experiments were conducted and the work piece after machining is inspected for surface finish and material removal rate as shown in the Table 3. The roughness values (Ra) were measured using MITUTOYO surface roughness tester (Figure 4). Corresponding to each Ra values and MRR the S/N ratios were calculated using smaller-the-better and larger-the-better characteristics. The main effects plots for S/N data means is obtained using MINITAB statistical software and the optimum condition for better surface finish and material removal rate is found from the grey relational grade (GRG) and plots. Grey relational grade (GRG) is calculated for the S/N ratios of Ra and MRR. The experimental runs are ranked in the descending order of GRG. Data analysis plot for means of GRG is obtained using MINITAB statistical software (figure 6).

**Table -3:** Experimental observations

| Run No. | Cutting parameters | | | | Output response | |
|---|---|---|---|---|---|---|
| | Cutting speed (RPM) | Feed rate (mm/rev) | Depth of cut (mm) | Nose radius (mm) | MRR ($mm^3$/min.) | SR (μm) |
| **1** | 225 | 0.10 | 0.1 | 0.4 | 204.3086 | 0.55 |
| **2** | 225 | 0.15 | 0.3 | 0.8 | 909.8447 | 0.71 |
| **3** | 225 | 0.20 | 0.5 | 1.2 | 1993.599 | 1.45 |
| **4** | 470 | 0.10 | 0.3 | 1.2 | 1267.043 | 1.30 |
| **5** | 470 | 0.15 | 0.5 | 0.4 | 3123.305 | 0.98 |
| **6** | 470 | 0.20 | 0.1 | 0.8 | 853.5557 | 1.47 |
| **7** | 715 | 0.10 | 0.5 | 0.8 | 3167.600 | 0.38 |
| **8** | 715 | 0.15 | 0.1 | 1.2 | 973.8700 | .47 |
| **9** | 715 | 0.20 | 0.3 | 0.4 | 3855.045 | 1.33 |

### 3.1 Analysis of Variance (ANOVA)

The purpose of ANOVA is to determine which cutting parameters significantly affect the quality characteristic (here, surface roughness and material removal rate). ANOVA tests the null hypothesis that the population means of each level are equal, versus the alternative hypothesis that at least one of the level means are not all equal. ANOVA calculation results for material removal rate and surface roughness are tabulated in the Table 4 and Table 5 respectively. The sums of squared deviations are calculated.

**Table -4:** ANOVA table for MRR

| Machining parameters | Degree of freedom (DOF) | Sum of squares (SS) | Mean sum of squares (MSS) | F | P | Contribution (%) |
|---|---|---|---|---|---|---|
| **Speed** | 2 | 4004447 | 2002224 | 2.53 | 0.283 | 30.61 * |
| **Feed** | 2 | 807344 | 403672 | 0.51 | 0.662 | 6.17 |
| **DOC** | 2 | 6685865 | 3342932 | 4.22 | 0.191 | 51.30 ** |
| **Nose radius** | 2 | 1582958 | 791479 | 1.00 | 0.179 | 11.92 |
| **Error** | - | - | - | - | - | |
| **Total** | 8 | 13080614 | | | | |

**Table -5:** ANOVA table for Surface Roughness

| Machining parameters | Degree of freedom (DOF) | Sum of squares (SS) | Mean sum of squares (MSS) | F | P | Contribution (%) |
|---|---|---|---|---|---|---|
| **Speed** | 2 | 0.17904 | 0.08952 | 0.34 | 0.747 | 12.18 |
| **Feed** | 2 | 0.67804 | 0.33902 | 1.29 | 0.438 | 46.16 ** |
| **DOC** | 2 | 0.08417 | 0.04209 | 0.16 | 0.862 | 5.73 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Nose radius** | 2 | 0.52744 | 0.26372 | 1.00 | 0.197 | 35.92 * |
| **Error** | - | - | - | - | - | |
| **Total** | 8 | 1.46869 | | | | |

Here, ** Most significant and * significant factors.

### 3.2 Grey Relational Analysis (GRA)

The Grey relational approach converts a multiple response process optimization problem into a single response optimization problem. The optimal parametric combination is then evaluated, which would result in the highest Grey relational grade. The optimal factor setting for maximizing the overall Grey relational grade can be performed using the Taguchi method.

In Grey relational generation, the normalized MRR and SR should follow the larger-the-better (LB) criterion. The higher value of the GRG corresponds to a relational degree between the Reference Sequence and the given sequence. The overall evaluation of the multiple performance characteristics is based on the grey relational grade (GRG). The grey relational grade is an average sum of the grey relational coefficient (GRC) corresponds to selected responses i.e. SR and MRR.

Using Grey relation equations and GRC values of surface roughness (Ra), material removal rate (MRR), Grey relational grade (GRG) is calculated. Therefore, a higher GRG means that the corresponding parameter combination is closer to the optimal. The mean response for the GRG and the main effect plot of the GRG are very important because the optimal process condition can be evaluated from this plot. The S/N ratio for MRR and SR and Grey Relational Grade (GRG) calculations are shown in the Table 6.

**Table -6:** S/N ratio for MRR and SR and Grey Relational Grade (GRG) calculations

| Run no. | Mean values | | S/N Ratios | | Grey Relational Grade (GRG) | | Rank |
|---|---|---|---|---|---|---|---|
| | MRR ($mm^3$/min.) | SR (µm) | MRR | SR | Mean | S/N Ratio | |
| 1 | 204.3086 | 0.55 | 5.27 | 46.21 | 0.5504 | -5.1864 | 3 |
| 2 | 909.8447 | 0.71 | 2.97 | 59.18 | 0.5027 | -5.9738 | 4 |
| 3 | 1993.599 | 1.45 | -3.23 | 65.99 | 0.4163 | -7.6118 | 5 |
| 4 | 1267.043 | 1.30 | -2.28 | 62.06 | 0.3348 | -9.5042 | 9 |
| 5 | 3123.305 | 0.98 | 0.22 | 69.89 | 0.4090 | -7.7655 | 6 |
| 6 | 853.5557 | 1.47 | -3.32 | 58.62 | 0.3533 | -9.0371 | 8 |
| **7** | **3167.600** | **0.38** | **8.40** | **70.01** | **0.8632** | **-1.2777** | **1** |
| 8 | 973.8707 | 1.47 | -3.35 | 59.77 | 0.3605 | -8.8618 | 7 |
| 9 | 3855.045 | 1.33 | -2.44 | 71.72 | 0.6828 | -3.3141 | 2 |

The ANOVA for grey relational grade (GRG) is tabulated as shown in the Table 7 and main effect plots are shown in Chart 1 and Chart 2.

**Table -7:** ANOVA for Grey Relational Grade

| Machining parameters | Degree of freedom (DOF) | Sum of squares (SS) | Mean sum of squares (MSS) | F | P | Contribution (%) |
|---|---|---|---|---|---|---|
| **Speed** | 2 | 0.10942 | 0.05471 | 1.50 | 0.400 | 43.51** |
| **Feed** | 2 | 0.03854 | 0.01927 | 0.53 | 0.654 | 15.31 |
| **DOC** | 2 | 0.03043 | 0.01522 | 0.42 | 0.706 | 12.09 |
| **Nose radius** | 2 | 0.07296 | 0.03648 | 1.00 | 0.559 | 28.99* |
| **Error** | - | - | - | - | - | |
| **Total** | 8 | 0.25136 | | | | |

Here, ** Most significant and *significant factors.

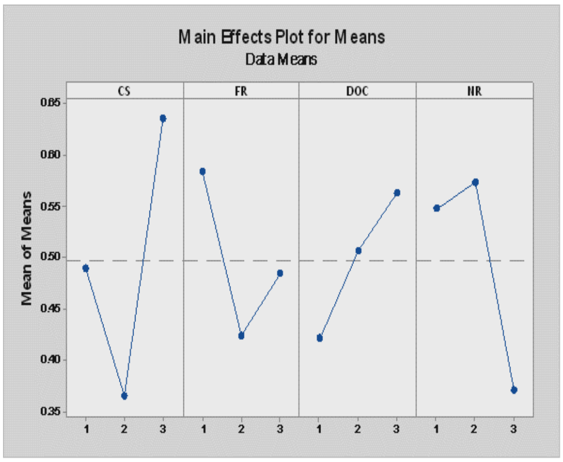


**Chart -1:** Main effect plot for GRG

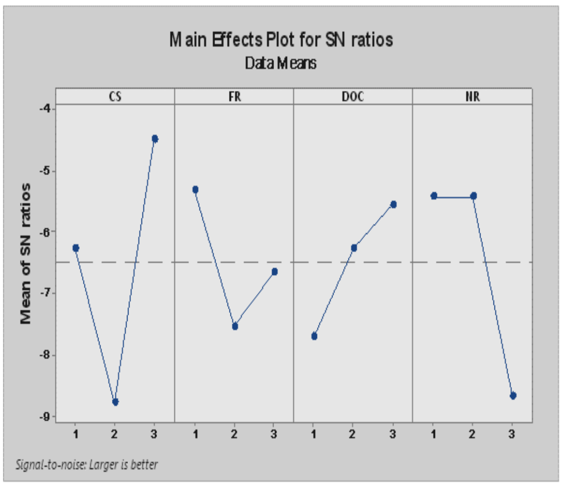


**Chart -2:** Data analysis plot for GRG

## 4. DETERMINATION OF OPTIMAL CONDITION

The grey relational grade calculated for each sequence is taken as a response for the further analysis. The larger-the-better quality characteristic was used for analyzing the GRG.A larger value indicates the better performance of the process i.e. closure to optimal condition. The S/N ratio is highest at optimal condition.

From the response table of GRG (Table 6), it is clear that, third level cutting speed, first level of feed rate, third level depth of cut and second level insert nose radius (i.e. 715 RPM, 0.10 mm/rev and 0.5 mm and 0.8 mm respectively) are the optimal parameters for the turning of Inconel 718 for above conditions. It can be also seen from Table 7 and Figure 5 and Figure 6 that speed is the most significant parameter in high speed machining of Inconel 718. After speed, the sequence of effect of process parameter in turning of Inconel 718 is insert nose radius, feed rate, and depth of cut.

Thus, the optimum combination is **V3-F1-D3-R2** i.e. 715 RPM, 0.1 mm/rev and 0.5 mm and 0.8 mm respectively.

### 4.1 Predictive Equation and Verification

After the optimal level of machining parameters has been identified, a verification test needs to be carried out in order to check the accuracy of analysis.

The predicted values of GRG, MRR and Ra at the optimal levels are calculated by using the prediction model. Applying this prediction model, predicted values of GRG, MRR and Ra at the optimum conditions are calculated as:

1. **ň (GRG) =** 0.805
2. **ň (MRR) =** 3029.48 $mm^3$/min.
3. **ň (Ra) =** 0.68 µm

The robustness of this parameter optimization is verified experimentally. This requires the confirmation run at the predicted optimum conditions. The experiment is conducted at the predicted optimum conditions.

## 5. VERIFICATIONS

### 5.1. Material Removal Rate (MRR)

The calculated value of MRR at the optimum condition is 3173.22 $mm^3$/min. The error in the predicted optimum value (3029.48 $mm^3$/min.) and the calculated value (3173.22 $mm^3$/min.) is only 4.53%.

### 5.2. Surface Roughness (Ra)

The calculated value of Surface Roughness at the optimum condition is 0.71 µm. The error in the predicted optimum value (0.68 µm) and the calculated value (0.71 µm) is only 4.35%.

Hence, so good agreement between the actual and the predicted results is observed. Since the percentage error is less than 5%, it confirms excellent reproducibility of the results. The results show that using the optimal parameter setting (V3-F1-D3-R2) a higher material removal rate is achieved with lower surface roughness.

## 6. RESULTS

The effect of three machining parameters i.e. Cutting speed, feed rate and depth of cut, nose radius and their interactions are evaluated using ANOVA and with the help of MINITAB 18 statistical software. The purpose of the ANOVA in this study is to identify the important turning parameters in prediction of Material Removal Rate and Surface roughness. Some important results come from ANOVA and plots are given as below. Table 8 shows that optimal values of surface roughness and material removal rate that lie between the optimal ranges.

**Table -8:** Optimal values of machining and response parameters

| Cutting Parameters | Optimal values of cutting parameters | Optimum levels of cutting parameter | Predicted optimum values | Experimental optimum value | Optimum range of MRR and SR |
|---|---|---|---|---|---|
| **Cutting speed**<br>**Feed rate**<br>**Depth of cut**<br>**Nose radius** | 715<br>0.10<br>0.5<br>0.8 | V3<br>F1<br>D3<br>R2 | MRR=3029.48<br><br>Ra=0.68 | MRR=3173.22<br><br>Ra=0.71 | 3029.48<br><MRR><br>3173.22<br>0.68<br><Ra><br>0.71 |

## 7. CONCLUSIONS:

This research work leads to following major conclusions:

1. Experimental observations under various cutting conditions for surface roughness and material removal rate were calculated.
2. Feed rate and nose radius are the most important parameters that affect the surface finish and Material Removal Rate (MRR) is greatly influenced by depth of cut followed by cutting speed in CNC turning process.
3. Optimization strategy developed and optimum conditions were found as V3-F1-D3-R2 (i.e. 715 RPM, 0.1 mm/rev and 0.5 mm and 0.8 mm respectively).
4. Verification test performed between actual and predicted results gives percentage error less than 5% which gives excellent reproducibility.

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